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Curbing global warming with phase change materials for energy storage

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ABSTRACT

The application of thermal energy storage (TES) system with phase change material (PCM) is an effective way for energy conservation and greenhouse gas (GHG) emission reduction. Global warming is increasing along with the energy consumption. Many researchers are concerned about this present global environmental problem for fossil-fuel burning. Thermal energy storage system with phase change material is observed as a potential candidate for mitigating this problem. This paper emphasizes the opportunities for energy savings and greenhouse-gas emissions reduction with the implementation of PCM in TES systems. For instance, about 3.43% of CO_2 emission by 2020 could be reduced through the application of PCM in building and solar thermal power systems. Similarly, energy conservation and GHGs emission reduction by other PCM applications for thermal comfort of vehicles, transport refrigeration, engine cold start, greenhouse and waste heat management are also presented. In addition, some present investigations on the performance improvement of the phase change materials are addressed.

Contents

1. Introduction

Worldwide, there is an increasing research interest on solar thermal energy as abundant, cheap, effective and clean energy. However, the absence of the sun light at night or scarcity on a gloomy day is challenging for continuous energy supply using solar thermal energy. In that context, scientists are looking for some way to store this vast energy to utilize it in the absence of sunlight. It could be the solution of the two present problems, such as the explored fossil fuels' depletion in high rate and the environmental impacts with global warming [1]. Thermal energy storage (TES) system with phase change material (PCM) could be a good option to reduce these problems. It is also mandatory to restrain the present global warming rate. Krewitt et al. (2007) reported that an increase of 2 °C of the global mean temperature above pre-industrial levels (13.1 °C) [2] is the optimum 'safe' level that could be envisaged. Global CO_2 emissions is required to be reduced by approximately 10 Gt/annum by the year 2050 to maintain its concentration within 450 ppm by volume (ppmv) in the atmosphere [3].

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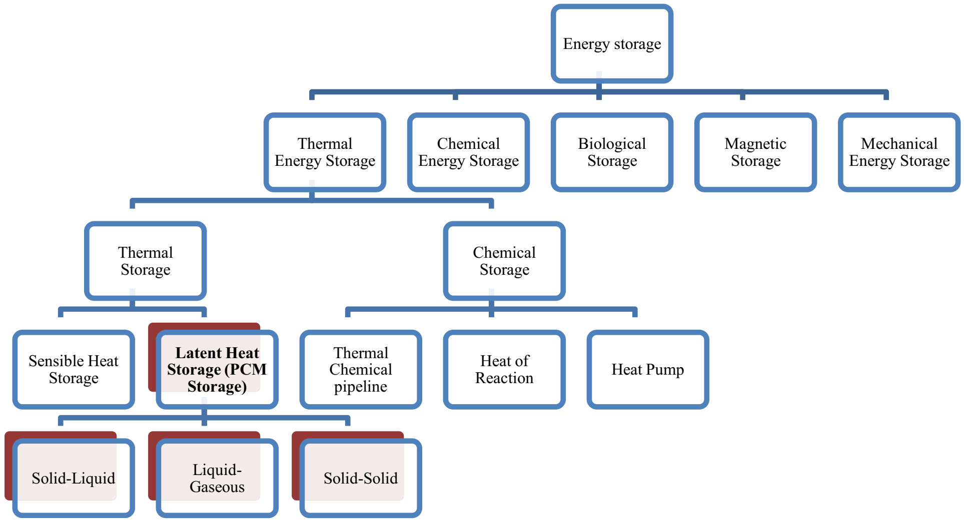

Fig. 1. Different type of energy storage systems [11,12].

In the last 150 years, radical development of industrialization and associated human activities have accumulated huge amount of GHGs to the atmosphere [4]. Alexiadis (2007) prepared a model to measure the influence of the CO_2 emission due to anthropogenic activities. He showed that the anthropogenic CO_2 emission has become the main driving force in global warming [5]. Greenhouse gases (GHGs) from the burning of fossil fuels, production, transportation and energy conversion result in climate changes by affecting the atmosphere chemically in the long term [6]. By the 1990s, more than 80% of the world energy was supplied by the hydrocarbon sources i.e., coal, oil and natural gas. The contribution of zero-carbon sources such as hydropower and nuclear power is so limited [7]. Energy associated CO_2 emission from fossil-fuel production and combustion is about 95% of the total emission [8]. Therefore, the development of sustainable energy conservation system is the prime need in the current energy demand context along with the environmental issues. Energy storage (ES) systems' potentiality is so attractive in that sense. These storage systems can store some kind of energy that can be utilized further. It is generally implemented to balance the energy demand with supply. An energy storage process works on three fundamental activities, such as charging (loading), storing and discharging (releasing) [9]. Moreover, one of the thriving techniques to store thermal energy is the PCM implementation. TES systems can help to enhance energy efficiency and mitigate energy related environmental effects especially in building heating, cooling and power generation. Therefore, TES systems could play a vital role for environment by mitigating emissions of CO_2, SO_2, NO_x, and CFCs [10].

In this present paper, the potentiality of PCM for TES to reduce fossil-fuel energy consumption and the associated GHGs emission are addressed with accumulating some research successes. Furthermore, some current researches on the enhancement of the performance of PCM are also introduced.

2. Energy storage—A possibility to mitigate global warming

The present frightening situation is influencing us for energy conservation and sustainable energy technology. Energy storage (ES) could be the best technological advancement so far for energy conservation. For instance, the abundant solar energy is cheap and easy to implement with the help of renewable technology, but it is hard to utilize the energy during the scarcity of sunlight. Here, energy storage system technology could be the only option to store this energy for instant or further implementation of such energy [11].

There are a number of thriving areas of researches in ES technology. Different types of energy storage systems and thermal energy storage systems with breakdown are shown in Fig. 1.

Among the stated different energy storage systems, an often-proposed solution to possible energy-resource shortage is the utilization of thermal energy storage (TES) technologies. In addition, the implementation of TES technologies could be also quite helpful in respect of environmental issues. For instance, California energy commission stated that TES could deduce 560 t of NO_x and 260,000 t of CO_2 statewide [10]. Considering the applicability, cost, energy consumption, conservation of fossil fuel and GHGs emission like CO_2, SO_2, NO_x, CFCs; the sustainable development of energy resources with TES is highly promising [13].

3. Thermal energy storage—A prospective energy storage system

The sustainable development must meet three basic things as economical, environmental and social [14]. In this aspect, thermal energy storage is one of the prospective energy storage systems for energy conservation. Thermal energy could be stored as chemical energy (reversible reactions), sensible heat, and latent heat (LH). Considering high-energy density and small temperature deviation from storage to retrieval, LH is highly promising [15]. TES systems store heat as latent heat for further use. This is a great opportunity to store available solar energy to use later for application. The storage material absorbs heat during melting while the material retains its temperature fixed at the melting temperature. Melting completes with absorbing the melting enthalpy and further heat transfer generates sensible heat storage. This melting enthalpy/latent heat is used to store energy as heat. Materials with a solid–liquid (melting) or solid–solid phase change which are applicable for heat or cold storage used as latent heat storage material or simply phase change material (PCM) [16]. Latent heat property of PCM is the most favorable for application as it behaves as a thermal switch. Reaching the melting point, the storage material continues the steady temperature for a while to be melted fully. This phase-change process enables the absorption of a large amount of heat without increasing the temperature of the system. A PCM can easily be applied into an existing thermal management system because the latent heat property of the PCM is a natural process that does not need any extra

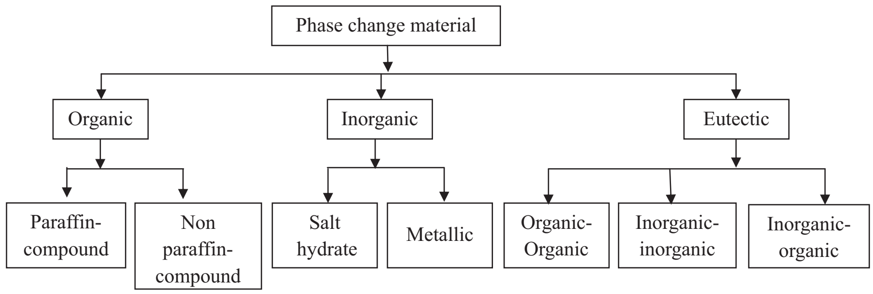

Fig. 2. Types of phase change materials (PCMs) [12].

Table 1
Some potential PCM for different thermal applications.

Types of PCM	Potential PCMs	Melting point range (°C)	Application	References
Organic	Paraffin, non paraffin compound	19–32	Building application	[21]
	Paraffin(RT 20,RT 26,RT 25,RT 30,RT 27,RT32) as commercial PCM	22–31	Building application	[21]
	Fatty acid(Stearic acid), commercial grade of acetamide and acetanilide	55.1, 82, 118.9	Solar cooking	[23]
	$Na_2CO_3 \cdot 12\ H_2O$	32–36	Engine cold start	[24]
	Graphite composite, Paraffin wax	52–55, 40–44	Lithium-ion battery cooling for electric vehicle	[19,25]
	Isomalt(($C_{12}H_{24}O_{11} \cdot 2H_2O$)+($C_{12}H_{24}O_{11}$)), Adipic acid, Dimethylol propionic acid, Pentaerythritol, AMPL ((NH_2)(CH_3)C(CH_2OH)$_2$),TRIS ((NH_2)C(CH_2OH)$_3$), NPG ((CH_3)$_2$C(CH_2OH)$_2$), PE (C(CH_2OH)$_4$)	147–260	Solar power generation	[26]
	Erythritol, NaOH	118, 320	Waste heat transportation	[27,28]
			Engine cooling	[29]
		112	Solar cooking	[23]
Inorganic	$MgCl_2 \cdot 6H_2O$, Hitec:KNO_3–$NaNO_2$–$NaNO_3$, HitecXL: 48%Ca(NO_3)$_2$–45%KNO_3 7%$NaNO_3$, Mg(NO_3) $\cdot 2H_2O$, KNO_3–$NaNO_2$–$NaNO_3$, 68% KNO_3–32%$LiNO_3$, KNO_3–$NaNO_2$–$NaNO_3$, Isomalt, $LiNO_3$–$NaNO_3$, 40%KNO_3–60%$NaNO_3$, 54%KNO_3–46%$NaNO_3$, $NaNO_3$, KNO_3/KCl, KNO_3, KOH, $MgCl_2$/KCl/NaCl, $AlSi_{12}$, $AlSi_{20}$, $MgCl_2$,NaCl, LiF, KF	115–897	Solar power generation	[26]
	Salt hydrate (Climsel C23,ClimselC24,STL 27,S27,TH 29,Climsel C32) as commercial PCM	22–31	Building application	[21]
	Calcium chloride hexahydrate, Glauber's salt (sodium sulphate decahydrate)	32–35	Greenhouse heating	[23]
	Sodium phosphate dibasic dodecahydrate ($Na_2HPO_4 \cdot 12H_2O$), Sodium Sulfate Decahydrate ($Na_2SO4 \cdot 10H_2O$), Calcium Chloride Hexahydride ($CaCl_2 \cdot 6H_2O$), Lithium Nitrate Trihydrate (Li–$NO_3 \cdot 3H_2O$), Zinc Nitrate Hexahydrate (Zn(NO_3)$_2 \cdot 6H_2O$)	29–48	Engine cold start	[30]
	$Na_2SO4 \cdot 10H_2O$, $NaOH \cdot H_2O$, NaOH, Ba(OH)$_2 \cdot 8H_2O$, $CaO \cdot 3H_2O$	32–64		[24],[31]
	KOH, 58.7%LiCl +41.3% KCl, $NaNO_3$, KNO_3	307–380		[24]
	Magnesium chloride hexahydrate	116.7	Solar cooking	[23]
Eutectics	Inorganic eutectics, organic eutectics	25–30	Building application	[21]

Table 2
Desired PCM properties [12,20,35].

Properties	Criteria
Thermal properties	Appropriate melting-solidification temperature
	High latent heat of fusion
	Better heat transfer
Physical properties	Desirable phase stability
	High density
	Minimum vapour pressure
	Less volume change
Kinetic properties	Super cooling resistance
	Sufficient crystallization
Chemical properties	Chemically stable
	Compatibility with materials of constructions
	Nontoxic
	Fire resistance
Economics	Cheap and available

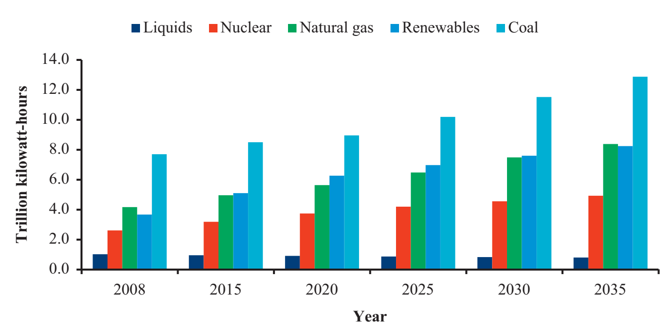

Fig. 3. World net electricity generation by fuel type, 2008–2035(trillion kilowatt-hours) [36].

energy input from the system [17]. These PCMs with the suitable latent heat property could be used for space heating, space cooling, power generation, green house heating, solar cooking, waste heat recovery system and latent heat storage exchanger [18]. Furthermore, phase change materials also could be applied to cool lithium-ion battery which is used in electric vehicles [19]. Hence, PCM applications' implementation may contribute in different sectors for energy conservation.

3.1. Types of phase change materials (PCMs)

There are mainly three types of PCMs suitable for different thermal applications like organic, inorganic and eutectic mixture of PCMs. Fig. 2 shows the types of PCMs. Organic PCMs are considered as chemically stable, free from supercooling, non-phase

Table 3
Competency of PCM to reduce energy consumption.

PCM application	PCM location in applications	Ability of energy savings
PCM application in Building for cooling and heating	Building applications e.g., PCM wall boards, trombe wall, PCM shutters, building blocks, air based heating systems, ceiling board, floor heating [21],gypsum board [38–40], radiant floor heating system [15], wall/wallboard, concrete [41], tile [42], cement [43], PCM ceilings for active heating and cooling [32], roof [44,45], free cooling through heat pipe [46],heat pump for heating [47].	a. Isaac and Vuuren made a model to explore the heating and cooling energy demand in the residential sector. It increased from about 27 EJ in 2000 to about 35 EJ in 2020 and almost 80 EJ in 2100 [48]. In this context, PCM application in building could save large amount of energy. b. Peippo et al. investigated with PCM wall using fatty acid as PCM and reported that 5–20% direct energy could be saved [33]. c. In 2002, IIR (International Institute of Refrigeration) reported that the refrigeration and air conditioning sectors had used about 15% of all electricity consumed worldwide [49]. Different types of PCM applications in building are available to reduce this consumption. d. Jeon et al. reported that in Korea, radiant floor heating used in residential buildings, consumed approximately 55% of the total residential building energy consumption in heating [50] and suggested to apply PCM to mitigate heating load. e. Li et al. also reported on U.S. buildings' energy consumption. They mentioned that about 48% of building energy was consumed by heating, ventilation, and air conditioning (HVAC) systems [51]. Hence, there is a great scope to reduce a large amount of energy consumption of U.S. using PCM for HVAC. f. Olarte et al. analyzed a case study for floor heating system with PCM. They discovered approximately 18% energy cost saving by PCM implementation [52].
Solar thermal power plant	Thermal storage tank, cascaded latent heat storages for steam generation during scarcity of enough sunlight, concentric solar power plant [26]	a. The Results from the scenario made by Greenpeace and the European Solar Thermal Power Industry Association (ESTIA) showed that electricity production, 54.6 TW h could be achieved in 2020 through solar thermal power. The South-Western United States, Central and South America, Africa, the Middle East, the Mediterranean countries of Europe, Iran, Pakistan and the desert regions of India, the former Soviet Union, China and Australia are the most potential countries for solar thermal power as necessary sun radiation is available there [53]. Figure 8 depicts that this electricity production would be about 0.35% of total electricity production by fuel. b Cavallaro reported on the availability of the sunshine in many parts of the world. He mentioned that it would be adequate to generate about 100–130 GW h of electricity per year from a surface area of 1 km^2 by solar thermal technologies. This amount of energy was tantamount to the yearly production of a traditional 50 MW power station fuelled by coal or natural-gas [54]. Gil et al. demonstrated the application of TES with PCM for power generation. They also addressed some existing alike power plant e.g., Solar Tres in Spain [26]. So, immediate steps are required for expanding more solar thermal power plant which can be more efficient by PCM use.
Thermal comforts in vehicle	Body of the vehicle [55], absorbing heat of exhaust gas and effluent coolant from an engine jacket cooler [56].	a. Mobile air conditioner (MAC) for thermal comforts in the passenger vehicle consumes 2.5–7.5%of the total fuel consumption, depending on some variability's [57]. b. In cars, air conditioning decrease fuel economy by 2.0 km L^{-1} (4.6 mile per gallon)) [58] Pieffer et al. patented an auxiliary heating and air conditioning system using PCM for thermal comfort in the vehicle [55]. Kata also demonstrated a plug-in TES system with PCM for air conditioning in the vehicle [56]. Thus PCM application could be used to reduce fuel consumption of vehicle.
Engine cold start	1. Catalytic converter of the engine[24] 2. Evaporator and pressure regulator of the LPG powered engine[30]	Boam with two liter saloon car on fuel consumption. He found that 60% of the supplied fuel energy was consumed during the first cycle to warm up the engine [59]. Gumus showed a solution to reduce this kind of energy consumption using PCM in catalytic converter [24]
Green house	Replacing heating device	a. Benli and Durmus analyzed different types of solar collector for greenhouse heating. They showed that collectors integrated with potassium nitrate (KNO_3) as PCM provided about %18–23 of total daily thermal energy to the greenhouse for 3 to 4 h comparing with the traditional heating systems [60]. b. Liu et al. studied greenhouse with PCM wall board and showed that 20% energy saving could be achieved during a whole winter [61]
Electronic cooling applications	Heat pipe	Weng et al. demonstrated a heat pipe module with PCM for electronic cooling and showed that the cooling module with tricosane as PCM can save 46% of the fan power consumption comparing with the conventional heat pipe [62].
Waste heat management	Heat storage container [27,28]	Kaizawa et al. investigated feasibility of the industrial waste heat transportantion system with the low melting point PCM, $CH_3COONa \cdot 3H_2O$ and high melting point, erythritol to office building, hospital, hotel, school etc. by container. They also compared PCM's energy requirement with conventional heating sources and found only 7.7% for hot-water supply and 12% for cold-water supply for erythritol [27]. Nomura et al. investigated the possible attribution of NaOH, PCM as latent heat storage for waste heat transportation and showed that only 8.6% energy needed as compared to conventional system requirement [28].

segregation material, non-corrosive, non-toxic and high latent heat of fusion capacitance for thermal energy storage. However, they are low thermal conductive and inflammable. Paraffin and non-paraffin are two types of organic PCMs. Non-paraffin organics are fatty acids, esters, alcohols and glycols [20]. Generally, organic PCMs are used for heating and cooling applications in building containing melting point range 20–32 °C [21].

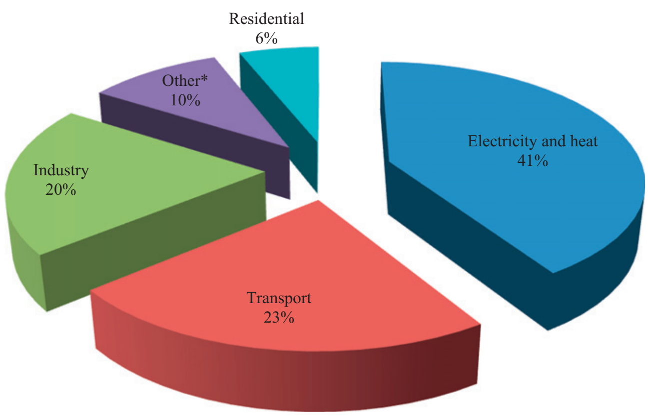

Fig. 4. World CO_2 emissions by sector in 2009 [63]. *Other includes Commercial/public services, agriculture/forestry, fishing, energy industries other than electricity and heat generation and other emissions not specified elsewhere.

On the other hand, inorganic PCM contains high latent heat of fusion, preferable thermal conductivity and fire resistance. They are also inexpensive. The disadvantages of inorganic PCMs' are corrosive, supercooling, segregation [20]. The most favorable inorganic PCMs are salt hydrates and their common application is solar-energy storages [22].

Eutectic mixtures or eutectics are generally three types like organic–organic, inorganic–inorganic and inorganic–organic mixtures. These mixtures melt and freeze congruently developing a composition of the component crystals during crystallization. Generally organic–organic, organic–inorganic and inorganic–inorganic eutectic PCMs are related with building applications [21].

The researchers are very concerned about the problems associated with the application of different types of PCMs to resolve. Mehling and Cabeza (2007) showed some way to reduce the problems regarding phase segregation, subcooling, low thermal conductivity, stability through gelling additive, adding nucleator, dispersing high thermal conductive material, and microencapsulation of PCMs, respectively [16]. Table 1 shows the applications of some potential PCMs for different applications.

3.2. PCM selection criteria for application

Phase change material (PCM) should possess some desired properties for application. There are some common techniques e.g., differential scanning calorimeter (DSC), differential thermal analysis(DTA) and T-history method setup which are used to measure thermal

Table 4
PCM potentiality to reduce GHGs emission.

Major PCM applications	Potentiality of PCM applications to reduce GHG emissions
Solar thermal power	The Results from greenpeace and ESTIA scenario 2002–2020 showed that 154 mt of CO_2 emission could be avoided through the solar thermal power [53]. U.S. Energy Information Administration projected in their Annual Energy Outlook 2011 that total CO_2 emission by coal, gas and liquid in 2020 would be 35198 million tones [36]. Hence, about 0.43% CO_2 emission could be avoided through the solar thermal power. The PCM for thermal energy storage could increase this contribution as the researchers showed the PCM application as an efficient candidate for the solar thermal power [26,64–73].
Building application	Isaac, M. and D.P. Van Vuuren made a model to calculate global CO_2 emissions from the residential sector for cooling and heating. They reported that emissions would be increased from about 0.8 Gt C in 2000 to about 1 Gt C in 2020 and about 2.2 Gt C in 2100 [48].About 3% of total projected 35.2 Gt CO_2 emissions by fuel in 2020 [36] could be tackled through PCM applications in building for heating and cooling.
Thermal comfort in vehicles	a. Uherek et al. reported in 2005 that 140 kt refrigerant emitted along with other emissions due to fuel combustion for mobile air conditioning (MAC) of vehicles which was more than double as high as projected in 1999 [57]. c. Levinson et al. reported that air conditioning (AC) in cars increased carbon monoxide (CO) emissions by 0.99 g km^{-1} and raise nitrogen oxide (NO_x) emissions by 0.12 g km^{-1}%) [58]. Plug-in thermal energy storage for the thermal comfort in the vehicle could be able to reduce about 20–30% of CO_2 emission [56].
Transport refrigeration	Transport refrigeration consists of eutectic systems. The systems use hollow tubes, beams or plates containing a eutectic solution as PCM for energy storage to deliver cooling effect. It could save up to 40% of the greenhouse gas emissions from the vehicle's engine as conventional diesel engine-driven vapour compression refrigeration systems emit [74].
Cold start of engine	a. Thermal energy storage device (TESD) can be used for pre-heating of IC engines before running. $Na_2SO_4 \cdot 10H_2O$ as phase change material used in the TESD and connected to the engine water jacket for pre-heating of an engine. This can solve the cold start problem as well as can reduce about 64% and 15% of CO and HC emissions, respectively [24]. b. Cold start problem could be removed using the embedded catalytic converter in PCM. A typical base metal catalytic converter embedded eutectic mixture of PCM $LiCl_2$/KCl and additives could be used to enhance the conversion efficiency during pre-heating. The conversion efficiency could be 73% for CO, 65% for hydrocarbon (HC) and 85% for NO_x [75]. c. Evaporator and pressure regulator surrounded with phase change material could reduce HC and CO emissions by 17.32% and 28.71%, respectively resolving engine cold start problem as well [30]. d. Bridgegate Ltd. Investigated latent heat storage (LHS) for BMW 5-series model vehicles. The HS containing the salt mixture $Mg(NO_3)_2$, H_2O and $LiNO_3$ reduced 30% unburnt HC and CO during the engine warming up [31].
Green houses	A conventional greenhouse (about 270 m^2) costs about 13t coal annually in Beijing DaXing district alone and as a consequence of coal burning huge CO_2 emission has been generated. By means of PCM application in green house can avoid this type of emission [60,61].
Solar cooker	Optimists calculated that 36% of the developing world's fuel wood using could be replaced by solar stoves. This fuel is responsible for huge CO_2 emission. TES technology could be applied for cooking with the available solar energy to reduce this emission [76].
Waste heat transportation	Kaizawa et al. compared industrial waste heat transportantion system with the erythritol PCM. He found that only 20.2% of CO_2 emission for hot-water supply and 26.6% for cold-water supply with erythritol PCM would be occurred comparing with the conventional heat sources used to transport waste heat PCM [27]. Nomura et al. explored 17.5% CO_2 emission with respect to the conventional system for waste heat transportation using NaOH PCM [28].

Table 5
Ongoing researches to enhance performance of PCM.

Properties	Some recent ongoing researches to enhance performance of PCM	References
Thermal conductivity	a. Wang et al. investigated the thermal conductivity of the paraffin with the dispersion of micron-size graphite flakes (MGMFs) and found improvement of thermal conductivity of the PCM. However, heat storage property and solidification time reduced in a small amount.	[77]
	b. Wang et al. prepared palmitic acid based phase change material with carbon nanotube (CNT) by mechno-chemical reaction with ball milling the blends of potassium hydroxide and the pristine CNT. It was found that PA/TCNT 1% mass fraction increased the thermal conductivity by 46% at 25 °C and 35% at 65 °C, respectively.	[78]
Charge/discharge rate of thermal energy	Arasu et al. studied numerical performance in regarding melting and freezing cycle of paraffin embedded with nano alumina (Al_2O_3) and the results showed that the melting ratio increased by 3.5%, 2.3% and 3.5% for paraffin wax with 2%, 5%, and 10% AL_2O_3, respectively. Solidification rate also enhanced by 28.1%, 29.8%, 33% for paraffin wax with the same fraction of AL_2O_3 individually than its pure form.	[79]
Supercooling	Zhang et al. decreased super cooling by dispersing multi-wall carbon nanotube (MWCNT) in to liquid *n*-hexadecane. They reduced supercooling of hexadecane PCM by 43% adding 0.1 wt% MWCNT.	[80]
Heat transfer characteristics	a. Kalaiselvam et al. minimized solidification time of 60% *n*-tetradecane: 40% *n*-hexadecane phase change material with the aluminium and alumina nano particles by 12.97% and 4.97%, respectively.	[81]
	b. Wu et al. minimized the liquidification and solidification times by 30.3% and 28.2%, respectively of a nano fluid PCM by adding Cu nanoparticle.	[82]
Inflammability	Song et al. prepared a form stable hybrid PCM with ethylene propylene diene terpolymer plastic (EPDM), paraffin, nano-MH and red phosphorus (RD). The hybrid PCM showed better fire resistant performance.	[83]

properties as thermal conductivity and latent heat of fusion [32–34]. Table 2 demonstrates the desired properties [12,20,35]

4. Potentiality of PCM—In reducing energy consumption and GHG emissions

The TES system is growing interest among the researchers for its applicability to reduce fossil-fuel consumption along with the GHG emissions. This is a great opportunity in context of present alarming trends of fossil-fuel consumption for electricity generation. To demonstrate the trends, Fig. 3 is showing the world net electricity generation by fuel type from 2008 and predicting 35 trillion kW h up to 2035.

On the other hand, air-conditioning generally accounts for a large amount of a building's energy consumption. TES with PCM could be one of the prominent candidates to reduce the heating and cooling load [37]. Moreover, this system also could be utilized in other energy consuming sectors. Cabeza et al. categorized PCMs based on their applications [35]. The researchers showed different PCM applications to reduce energy consumption (Table 3).

Besides, TES with PCM also can contribute in reducing GHGs emissions through energy conservation. It is mandatory to reduce fossil-fuel consumption which is responsible for the most devastating CO_2 emissions to mitigate global warming. Fig. 4 depicts that electricity and transport sectors generated approximately two-thirds of global CO_2 emissions in 2009.

TES systems could be one of the candidates to solve these issues. The researchers are getting more interest following the potentiality of TES systems through PCM success rate. Table 4 shows some achievement to reduce GHGs emission with PCM for different applications.

5. Recent researches on PCM for performance enhancement

Considering the PCMs' potentiality, the researchers are trying to enhance the performance of PCMs to achieve more efficient TES systems. Table 5 shows the current researches on the improvement of thermo physical properties of PCM.

6. Conclusion

A comprehensive review on previous studies about the potentiality of PCMs for TES in respect of energy saving and GHGs emission reduction is addressed in this paper. The followings are the conclusive remarks about the findings:

- About 3% of total CO_2 emissions by fuel, projected in 2020 could be reduced with PCM applications in building for heating and cooling.
- 54.6 TW h electricity generations would be possible through solar thermal power. Hence, about 0.43% of total CO_2 emission by fuel could be avoided in 2020 through PCM applications in solar thermal power systems.
- PCM implementation for thermal comforts in vehicle can reduce refrigerant emissions besides fossil-fuel consumption. At present, more than 140 kt of refrigerant is emitting for this purpose. This application also can reduce GHGs emission which is being emitted by engine cold start.
- Furthermore, the researchers have brought to light the performance of PCM for the transport refrigeration, greenhouse, waste heat management etc. They have showed their success in these applications in respect of energy conservation and GHGs emission reduction.

7. Future outlook

Phase change materials in many energy applications have attracted extensive research as showed above because of its potentiality. However, a lot of work still needs to be done to be able to apply these concepts in a reliable and practical way for energy conservation and GHGs emission reduction.

(a) **Thermphysical properties**: Thermophysical properties of PCMs are required to improve more. Dispersion of nanoparticle has good potentiality for performance enhancement of PCM. Hence, research is still needed on nanoparticle dispersed phase change material.
(b) **PCM application in existing energy system**: Effective designs with cost feasibility analysis are needed for retrofitting with PCM application in existing conventional energy systems to reduce present GHGs emission.

(c) **Cost**: Cost of PCMs is also required to make affordable for the applications in the system.

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